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AN EXPERIMENTAL STUDY OF CHARACTERISTIC COMBUSTION-DRIVEN FLOWS FOR CFD VALIDATION

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SUMMARY/OVERVIEW

The application of laser-based diagnostic techniques has become commonplace to a wide variety of combustion problems (for example, Ref. 1). New insights into combustion phenomena at a level previously unattainable has been made possible by non-intrusive measurements of velocity, temperature, and species. However, due to the adverse conditions which exist inside rocket engines, relatively few studies have addressed these combustion environments.[2]

The high pressure, high speed, combusting environment in a rocket engine prohibits the application of several measurement techniques. However, in the rocket community, there is a critical need for rocket flowfield data to validate Computational Fluid Dynamic (CFD) codes. Currently at Penn State, there is an effort to obtain flowfield measurements inside a rocket engine. Velocity measurements have been made inside the combustion chamber of a uni-element (shear coaxial injector) optically accessible rocket chamber at several axial locations downstream of the injector. These measurements, combined with future measurements, will provide benchmark data for CFD code validation.

TECHNICAL DISCUSSION

The velocity measurements were made in an optically accessible rocket chamber at Penn State's Cryogenic Combustion Laboratory. This facility is capable of supplying gaseous hydrogen (GH_2) and gaseous oxygen (GO_2) at mass flow rates up to 0.11 kg/s (0.25 lbm/s) and 0.45 kg/s (1.0 lbm/s), respectively. The uni-element rocket chamber used is modular in design and can be easily configured to provide optical access along the chamber length. A cross-sectional view of the rocket assembly is shown in Fig. 1. The rocket chamber is comprised of several interchangeable sections which include the injector assembly, igniter, window and blank sections, and a nozzle assembly. The windows are protected from the hot combustion gases by a gaseous nitrogen (GN_2) curtain purge which flows across the interior window surfaces.

A shear coaxial injector was used to introduce the propellants into the combustion chamber. The nominal mass flow rate of GH_2 through the annulus of the shear coaxial injector was 0.011 kg/s (0.025 lb/s), while the GO_2 mass flow rate through the central tube of the injector was 0.045 kg/s (0.1 lb/s), resulting in an O/F mass flow rate

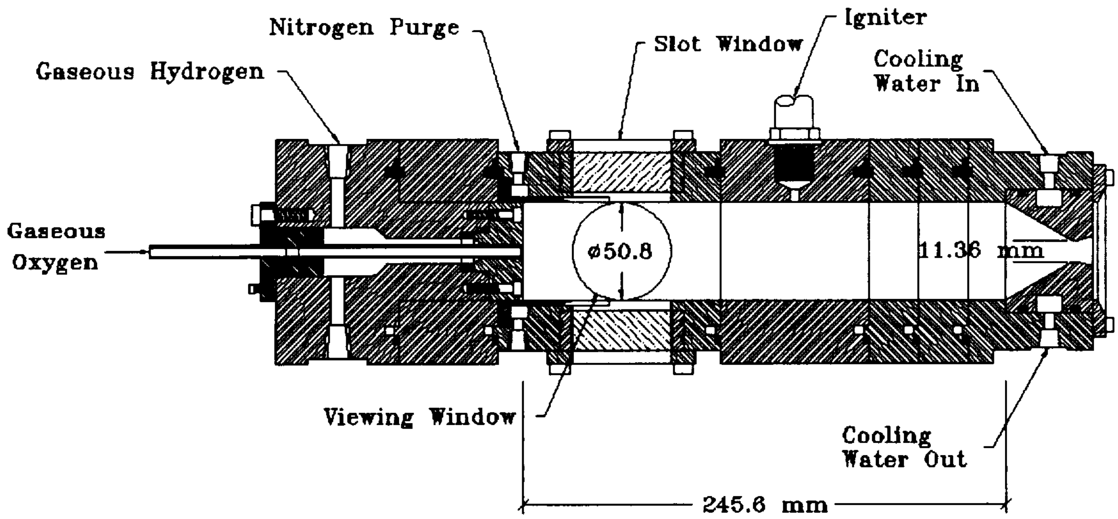

Fig. 1. Cross-sectional view of the optically accessible rocket chamber. The chamber is modular in design and allows for varying the chamber length, injector assembly, window-section location and nozzle assembly. The interior of the chamber is 50.8 x 50.8 mm. For the results presented here, a shear coaxial injector was used. The GO_2 post has an inner diameter of 7.75 mm (0.305 in.) and is not recessed with respect to the injector face. The fuel annulus has an inner diameter of 9.53 mm (0.375 in.) and an outer diameter of 12.7 mm (0.5 in.). The chamber length and nozzle throat diameter are 245.6 mm and 11.36 mm, respectively.

ratio of four. The corresponding mean injection velocities of GO_2 and GH_2 into the rocket chamber were 57 m/s (187 ft/s) and 194 m/s (636 ft/s), respectively. The combination of these mass flow rates with a nozzle having a throat diameter of 11.36 mm (0.447 in.) produced a chamber pressure of 1.31 MPa (190 psia). A rocket firing was four seconds in duration. Velocity measurements were taken from 1.4 to 3.9 seconds into the rocket firing to avoid measuring velocities during the start up and shut down transient periods.

Laser Doppler Velocimetry (LDV) was used to measure the velocity field in the rocket. The LDV system consists of a transmitter and receiver, each of which was inclined at an angle of 15° with respect to the horizontal plane to avoid problems with reflections. A probe volume was formed inside the rocket chamber by splitting an argon ion laser beam ($\lambda = 514.5$ nm) into two beams and focusing them to an intersection. The optics were mounted on translation stages to allow the probe volume to be traversed vertically through the flowfield. In order to reject light from the luminous flame of the GH_2/GO_2 flow, a 10 nm bandpass filter centered around 514.5 nm was placed in front of the receiving optics. Fluidized bed seeders were used to introduce aluminum oxide (Al_2O_3) seed particles into the GH_2/GO_2 flows. A small portion of the main gas flow is diverted into the seeder and flows through a porous plate (this plate traps particles greater than 5 μm) on which seed particles are placed. This secondary flow entrains seed particles as it exits through the top of the seeder to recombine with the primary flow. The GH_2 and GO_2 flows were seeded individually.

The measured radial velocity profiles, along with the visible flame front, at the three axial measurement locations downstream of the injector face, viz., 25.4, 50.8 and 127 mm (1, 2 and 5 in.), are presented in the three inset graphs in Fig. 2. The radial velocity profile at the closest axial measurement location, 25.4 mm (1 in.), shows that in the shadow of the central GO_2 post of the injector, the mean velocity at the centerline is the same as the injection GO_2 mean velocity, i.e. about 57 m/s (187 ft/s), suggesting that the core of the GO_2 flow has not been affected by shear from the higher velocity GH_2 flow. Only the GO_2 flow was seeded for velocity measurements in this central region. For increasing radial distance in both directions, the mean velocity increases to a peak of about 120 m/s (394 ft/s), and then decreases. For velocity measurements in this outer region, only the GH_2 flow was seeded. The peak velocity is significantly lower than the injection GH_2 velocity (194 m/s) and occurs radially outward from the shadow of the injector's annulus, suggesting that the GH_2 flow is diffusing with radial distance and mixing with both GO_2 and the net outward mass flux of the combustion product, gaseous H_2O. Further inspection of the velocity profile at the 25.4 mm (1 in.) location also shows that in the mixing layer between the two flows, the measured mean velocity at a point differs depending on which flow was seeded. This is a reflection of the unsteady nature of the flame front and will be discussed later.

The radial velocity profile at the middle axial measurement location, 50.8 mm (2 in.), shows that the mean velocity in the central core is still the same as the injection GO_2 mean velocity, i.e. about 57 m/s (187 ft/s); however, here the velocity profile is more uniform suggesting that the wall effects on the turbulent velocity profile from the central GO_2 tube have relaxed with axial distance. Away from the central core, the mean velocity peaks at a maximum of about 80 m/s (262 ft/s) at a greater radial location than for the 25.4 mm (1 in.) axial measurement location, and then decreases with radial distance. Mean velocities at this axial location were measured radially up to about 20 mm (0.79 in.), as compared to about 15 mm (0.59 in.) for the 25.4 mm (1 in.) axial location, showing that the flowfield expands with axial distance. In terms of seeding, seed in the GH_2 flow was sufficient for making mean velocity measurements in the shadow of the central tube. The seed particles can be viewed to represent a passive scalar,[3] i.e. the GH_2 flow seeding marks locations where hydrogen is present either as H_2 or H_2O, the combustion product. This indicates that at this axial location, hydrogen in the form of reactant GH_2 or product, gaseous H_2O is present in the central regions of the flowfield. Conversely, radial locations where velocity measurements are made by just seeding the GO_2 flow marks the presence of either GO_2 or gaseous H_2O.

The third velocity profile shown in Fig. 2 is for the 127 mm (5 in.) axial position. Here, the velocity in the central core is still about the same as the mean GO_2 injection velocity. However, unlike the velocity profiles at the other two axial measurement locations, the peak velocity is maximum at the centerline and relaxes with radial distance. Near the wall, the velocity profile shows a small increase from 25 m/s (82 ft/s) at a radial distance of -21 mm (0.83 in.) to almost 30 m/s (98 ft/s) at the next radial location. This is probably due to the nitrogen (GN_2) purge flow at the bottom of the combustion chamber for the slot windows. Note that the entire velocity profile was measured by just seeding the GH_2 flow.

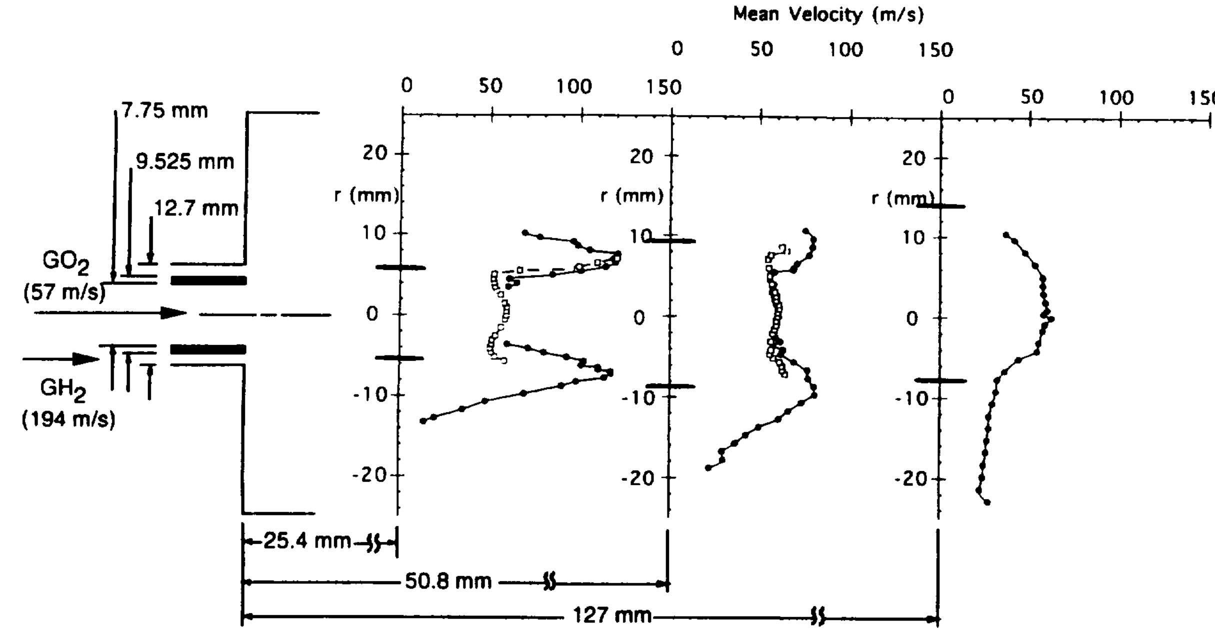

Fig. 2. Mean velocity profile measurements at three axial locations, 25.4, 50.8, and 127 mm (1, 2, and 5 in.), downstream of the injector face. The visible flame front (measured from 35 mm photographs) at each axial measurement location is indicated by the lines marked on the radial axes. The injector housing is also shown for reference. Note that the axial distances are not to scale. The hollow square (□) and solid circle (●) symbols correspond to GO_2 and GH_2 flow seeding, respectively.

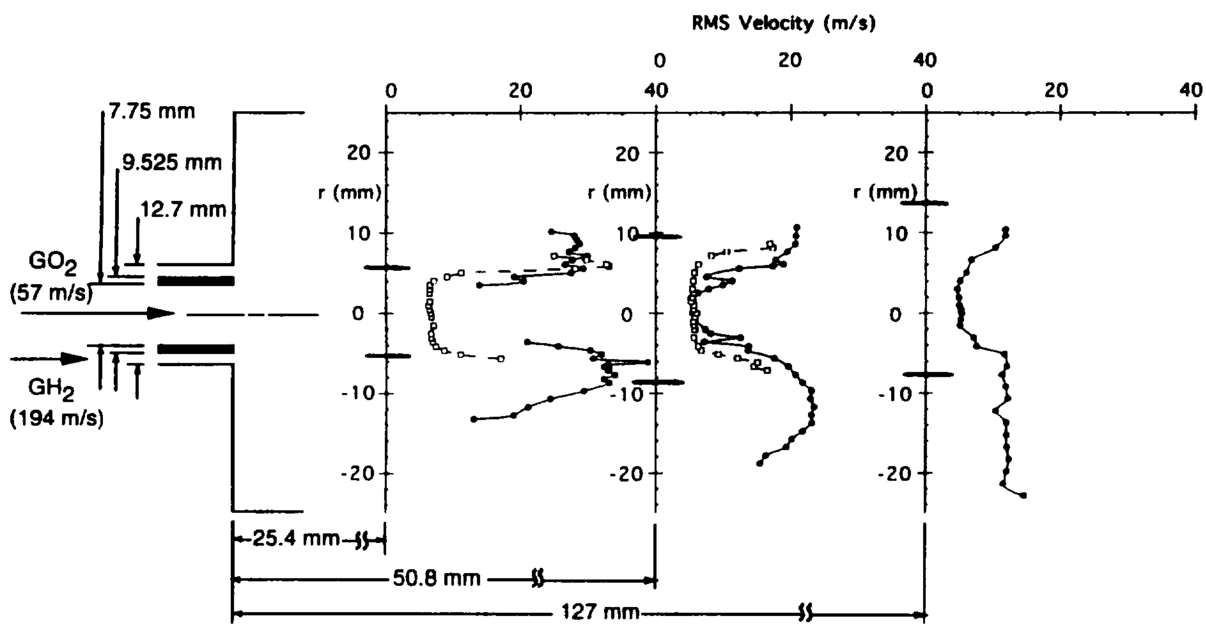

Fig. 3. Root mean square velocity profile measurements at three axial locations, 25.4, 50.8, and 127 mm (1, 2, and 5 in.), downstream of the injector face. The visible flame front (measured from 35 mm photographs) at each axial measurement location is indicated by the lines marked on the radial axes. The injector housing is also shown for reference. Note that the axial distances are not to scale. The hollow square (□) and solid circle (●) symbols correspond to GO_2 and GH_2 flow seeding, respectively.

The corresponding root mean square (RMS) velocities are plotted in a similar manner in Fig. 3. In the central core, the root mean square velocity is about 6 m/s at all three axial measurement locations yielding a turbulent intensity value of about 0.1, or 10%. Fully developed pipe flow turbulent intensities are about 0.05, or 5%,[4] indicating that the incoming flow has a higher turbulent energy content and/or the combustion enhances the turbulence levels. In the peak velocity region at the first measurement location, the mean velocity is about 120 m/s (394 ft/s) with a corresponding root mean square velocity of about 30 m/s (98 ft/s) resulting in a turbulent intensity of about 0.25 or 25%. The higher turbulent intensity value here is probably a result of both combustion and the unsteady nature of the flow. A similar value of turbulent intensity is also obtained for the peak velocity region at the second axial location (mean velocity and RMS velocity are 80 m/s (262 ft/s) and 20 m/s (66 ft/s), respectively). At the outer regions of the furthest axial measurement location, both the mean velocity and the RMS velocity drop off in comparison to the other measurement locations; however, the rate of drop off is significantly higher for the mean velocity, resulting in a turbulent intensity of about 0.4 or 40% (mean velocity and RMS velocity are 25 m/s (82 ft/s) and 10 m/s (33 ft/s), respectively).

Fig. 4. Image of light scattered from seed particles originally entrained in the GO_2 flow. A laser light (λ=532 nm) sheet introduced into the rocket chamber was used to illuminate the seed material.

Images were also taken with a CCD camera of the scattered light from the seed particles inside the rocket chamber under conditions in which only the GO_2 flow was seeded. A typical image is shown in Fig. 4. In the figure, white areas represent locations where oxygen is present either as GO_2 or H_2O. The image (and other similar images) clearly shows that the oxygen region does not have smooth edges, but is characterized by highly irregular protuberances. This suggests that the mixing region is characterized by large scale turbulent structures that seem to eject from the central oxygen rich region in a manner analogous to bursts in the near wall region of a turbulent boundary layer. Single point velocity measurements in this type of mixing layer will therefore vary depending on the seeding method, i.e, seed in GH_2 or GO_2 flow, and is observed to be true for the velocity profile measurements described earlier. Similar observations regarding the effects of seeding on velocity measurements have been reported for turbulent diffusion flame studies.[5]

SUMMARY

Initial measurements on the evolution of the velocity field in a rocket-like chamber are reported. These results demonstrate that laser-based diagnostics can be effectively applied to *in-situ* measurements for uni-element rocket chamber geometries. The velocity measurements indicate that the evolution of the reacting flowfield for the shear coaxial flow studied involves a highly unsteady turbulent combusting flow.

Comparisons between the rocket flowfield and turbulent diffusion flame studies conducted at atmospheric pressure conditions indicate that the turbulent intensities and unsteady nature of the flows are similar. Additional velocity measurements, involving two dimensions, as well as other measurements, including temperature and species, will provide a better understanding of this complex combusting flowfield.

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